9

DEVELOPMENT OF A 100 WATT S-BAND TRAVELING-WAVE TUBE

By
L. A. Roberts
M. V. Purnell

14 April 1967

Contract No. 951299

"This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

Quarterly Report No. 1

Watkins-Johnson Company
3333 Hillview Avenue
Palo Alto, California

DEVELOPMENT OF A 100 WATT S-BAND TRAVELING-WAVE TUBE

By
L. A. Roberts
M. V. Purnell

14 April 1967

Contract No. 951299

"This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

Quarterly Report No. 1

Watkins-Johnson Company
3333 Hillview Avenue
Palo Alto, California

PRECEDING PAGE BLANK NOT FILMED.

ABSTRACT

This report is the first quarterly progress report on the development of a 100 watt, 55 percent efficiency, 2.3 GHz traveling-wave tube for space applications. During this quarter, program plans and schedules were laid out, tube designs were completed and materials were ordered. Design of the electron gun was completed, a gun was constructed and the beam profile was measured in the gun testing equipment. Preliminary electrical tests of the helix structure were made and design decisions were made on the helices for initial tubes. Various mechanical details of the tube were decided and assembly procedures worked out. This report gives the details of the design and construction decisions that were made.

Preparations are complete for construction of the first tubes next quarter.

PRECEDING PAGE BLANK NOT FILMED.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

In planning for future space communications systems, it has become abundantly clear that these future systems will need the capability of higher data rate transmission than is presently available. These needs arise from the projected requirements for real time television transmission, wideband multichannel telemetry, improvement in data transmission rate from deep space, and the requirements for point to point communication between spacecraft or between spacecraft and ground with omnidirectional antennas. Improvements are possible in almost all aspects of the system which include receivers, transmitters, antennas and encoding systems.

One very important system parameter which can be upgraded is the RF power output of the spaceborne transmitter. There are definite limitations upon this power based upon the present technology of the primary spacecraft power systems. For short term, manned spacecraft missions where primary power is based upon fuel cell technology, relatively large amounts of primary power are available. In unmanned, earth orbit missions of long duration where energy generation is based upon solar cell technology, primary power is much more precious. Deep space missions find primary power limitations are even more critical, particularly those missions into the solar system in the direction away from the sun, where primary power is again based upon solar cell technology. In this latter case, the need for increased transmitter power increases as well because of the vast distances over which communication must take place.

With a limited primary power budget and the simultaneous need for increased transmitter power, the importance of conversion efficiency of the transmitter system becomes very clear. It is with the above requirements in mind that the development program for a high efficiency 100 watt traveling-wave tube suitable for use in a spaceborne transmitter was begun. The highest power used in a deep space transmitter to date amounts to approximately 10 watts of RF power. The goals of the present development represent a tenfold increase in power output and a doubling of the efficiency over that of previously used devices.

Tube Requirements

The complete requirements of the traveling-wave tube are given in JPL Specification No. GMY-50467-DSN. The main requirements are summarized as follows:

RF PERFORMANCE

Frequency	2295 ± 15 MHz
Power Output	100 watts min.
Efficiency	55 %
Gain	30 dB

MECHANICAL REQUIREMENTS

Weight and Size	Minimum compatible with good design practices
Cooling	Conduction
Focusing	PPM

ENVIRONMENTAL REQUIREMENTS

Temperature Range	-10 to +75^{o} C
Vibration	14 g rms,18 sec; then 5 g rms noise + 2 g rms sine 15-40 cps + 9.0 g rms sine 40-2000 cps for 600 sec; then 14 g rms, 18 sec
Shock	200 g, 0.5 to 1.5 ms
Acceleration	14 g, 5 min.
Pressure	Extended periods at 10^{-9} Torr or less

Watkins-Johnson Background in Space Tube and High Efficiency TWT Work

Watkins-Johnson Company has done work in a number of areas which have led directly into this present work. These include:

1. Development of a wide range of traveling-wave tube amplifiers which contain tubes, power supplies and other components designed specifically for space use. These included the development of the traveling-wave tubes as well as the complete amplifier system. These have been in the S-Band, C-Band and X-Band ranges.

2. Development programs which led to the development of the WJ-274 and the WJ-274-1. The WJ-274 has produced 40 percent overall efficiency at the 25 watt level at 2.3 GHz; the WJ-274-1 is fully qualified for space application.

3. A research program into the techniques for achieving high efficiency in traveling-wave tubes sponsored by the U. S. Army Electronics Command. In the course of investigations on this latter program, experimental traveling-wave tubes have been built at 1.0 GHz which have yielded up to 51 percent efficiency at the 20 watt power level. These efficiencies have been achieved by two separate methods.

One technique, called the "two helix" or "two-stage helix" approach, consists of a conventional traveling-wave tube followed by a second short section of lossless (no attenuator) helix, which interacts with the electron beam exiting from the first helix. This second or output section of helix is driven by the power output of the first stage. The output helix is also isolated in voltage from the first section and can be operated at a higher potential. Depressed collector operation is used to recover as much beam energy as possible.

Another technique which has demonstrated comparable efficiencies (i.e., greater than 50 percent) with a single helix voltage has also evolved from the USAECOM program. This called the "positive taper helix" approach. This technique involves a combination of large overvoltage operation of the helix and an increased helix pitch at the output end of the helix. Both the "two helix" and "positive taper" efficiency improvement techniques were studied in the frequency band around 1.0 GHz and the electron beams were focused with solenoidal magnetic fields.

This present program for a 100 watt tube and a parallel program for NASA Langley Research Center to study means of achieving very high efficiencies with the WJ-274, are designed to apply these techniques to a PPM focused space type TWT. The JPL and Langley tubes also represent hardware with intended spacecraft use.

II. GENERAL ELECTRICAL DESIGN OF THE TUBE

Two tube designs were calculated: one for the interim design and one for the final tube design. The interim design was based upon a beam efficiency of 30 percent. This is an achievable beam efficiency with a single uniform helix based upon the technology of the WJ-274, where beam efficiencies of 30 to 33 percent have been demonstrated. The final tube design is based upon a beam efficiency of 45 percent and the use of more complex structures. This is only slightly above the value achieved on the high efficiency study program. The design parameters of the interim and final tube designs are listed in Tables II and III. The interim design will be used to prove out the mechanical, electrical and beam focusing designs. Environmental and thermal tests can be run on this design which with depressed collector operation should achieve in excess of 40 percent overall efficiency. Once this tube has been established as a test vehicle, the construction of the higher efficiency designs can proceed.

TABLE I

Specification Listing the Anticipated Performance of the Final Tube

PERFORMANCE	
Frequency range	2.25 - 2.35 GHz
Power output	100 watts
Saturation gain	30 dB min.
Overall efficiency	55% min.
ELECTRICAL REQUIREMENTS	
Heater voltage	5 volts
Heater current	.8 amps.
Anode voltage	2900 volts
Anode current	.5 mA
Helix I Voltage	2200 volts
Helix I current	10 mA
Helix II voltage	2850 volts
Helix II current	10 mA
Collector voltage	2200 volts
Collector current	66 mA
Focusing means	PPM
MECHANICAL CHARACTERISTICS	
Cross-section (excluding connectors)	1 x 1 inch
Length	20 inches
Weight	3 pounds
RF Connector	OSM
Cooling	Conduction

TABLE II

List of Design Parameters for Interim Tube Design

Power Output	100 watts
Perveance	.51 micropervs
Beam Efficiency, ηo	30 percent
Beam Voltage	3360 volts
Beam Current, I_o	99 mA
Normalized Beam Velocity, u_o/c	.1149
Normalized Helix Velocity, v/c	.089
Pierce Velocity Parameter, b	3.05
Center Frequency, f_o	2.3 GHz
Helix Diameter, 2a	.131 inches
Beam Diameter, 2b	.071 inch
Beam Current Density, J_o	3.77 A/cm^2
Brillouin Focusing Field, B_{br}	367 gauss
Peak ppm Field, $\hat{B}_{zo}$	826 gauss
Guide Wavelength, λg	1.16 cm
Plasma wavelength, λp	1.805 inches
Normalized Circuit Radius, γa	0.908
Dielectric Loading Factor, DLF	0.68
Helix Pitch Angle, CotΨ	9.88
Helix Turns/Inch	23.8
Normalized Circuit Radius, ka	.0808
Impedance Reduction Factor, F	.261
Pierce Impedance, K	85.0 ohms
Pierce Gain Parameter, C	.0855
Pierce Space Charge Parameter, QC	.321

Figure 1 shows the beam voltage and current versus perveance for a 100 watt output design. Efficiency is shown as a parameter. The final and interim design points are shown on this curve. The perveance of .51 micropervs was selected as the design perveance because the tubes could be focused using Alnico 8 magnets. The design parameters in Tables II and III result from the selection of the perveance and beam efficiency of the interim and final design.

Figure 2 shows the helix dispersion characteristics as measured. This information was used to determine the design parameters for the interim tubes.

Magnet Design

A perveance was chosen which allows the tube to be focused using Alnico 8 magnets. The use of Alnico 8 magnets will allow the tube to be operated over wide temperature ranges with no degradation of focusing or RF performance, since the Alnico 8 magnets have a low temperature coefficient. In the design of a PPM stack it is necessary that the PPM stack produce the required focusing field and that the period of the PPM stack be sufficiently short, relative to the scalloping wavelength of the beam, to prevent defocusing. Both of these are easily achieved using the Alnico 8 magnets and a perveance of .51 micropervs.

Figure 3 shows the geometry of the PPM stack, and Table IV lists the magnetic design for both the interim tube design and the estimated final tube design. The ratio of scalloping wavelength to period is listed for both designs. The scalloping wavelength has been determined by using velocity of the slowest electron which exists under saturated RF drive. A pole piece configuration shown in Fig. 3 will be used in the interim tube design, although we initially considered a single hub pole piece which could be drawn out of sheet stock. The interim pole pieces will be machined two hub pole pieces. These can later be made up of two single hub stamped or drawn pole pieces. Figure 4 shows the various type pole pieces mentioned above.

The magnets were ordered approximately half way through the reporting period, and the best delivery we could obtain was 16 weeks. These magnets were ordered from two different vendors because the program is very dependent on receiving these magnets as soon as possible. By using two vendors, we hope to decrease the possibility of late vendor delivery. In addition, an interim magnet is being ground from off-the-shelf material. These magnets are constructed of four pieces per ring. It is hoped that the initial tube test could be conducted with these interim magnets.

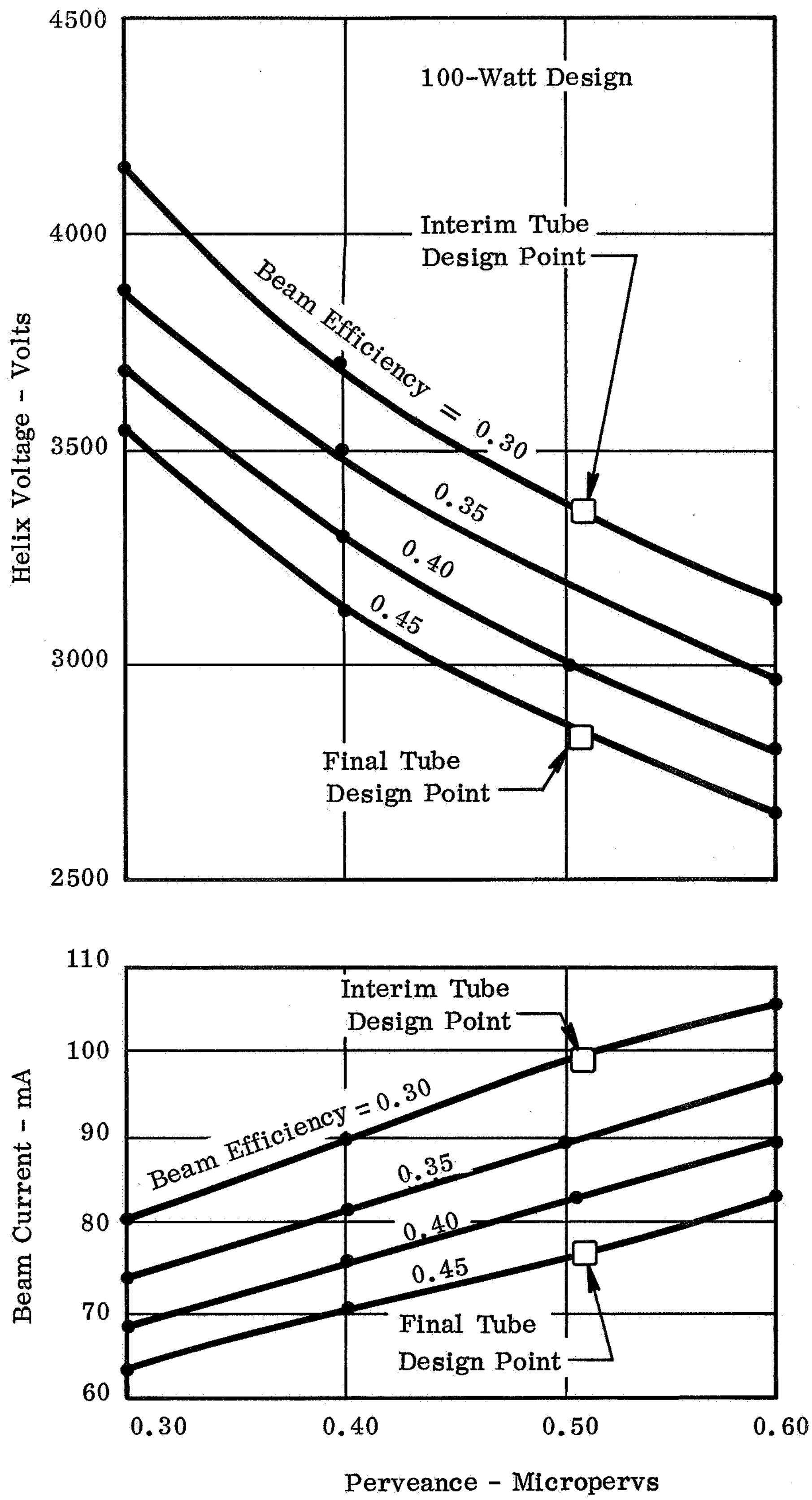

Fig. 1 - Beam voltage and current versus perveance for 100 watt RF design. Efficiency is shown as a parameter.

TABLE III

List of Design Parameters for Final Tube Design

Power Output	100 watts
Perveance	.51 micropervs
Beam Efficiency, η_o	45 %
Beam Voltage	2850 volts
Beam Current, I_o	78 mA
Normalized Beam Velocity, u_o/c	0.1057
Normalized Helix Velocity, v/c	0.0759
Pierce Velocity Parameter, b	4.25
Center Frequency, f_o	2.3 GHz
Helix Diameter, 2a	.1177 inch
Beam diameter, 2b	.0706 inch
Beam current density, J_o	3.08 A/cm^2
Brillouin Focusing Field, B_{br}	354 gauss
Peak ppm field, $\hat{B}_{zo}$	707 gauss
Guide Wavelength, λg	.989 cm
Cyclotron Wavelength, λp	1.768 inches
Normalized Circuit Radius, γa	0.95
Dielectric Loading Factor, DLF	0.79
Helix Pitch Angle, Cot Ψ	13.31
Helix Turns/Inch	36
Normalized Circuit Radius, ka	.072
Impedance Reduction Factor, F	.34
Pierce Impedance, K	130
Pierce Gain Parameter, C	0962
Pierce Space Charge Parameter, QC	.232

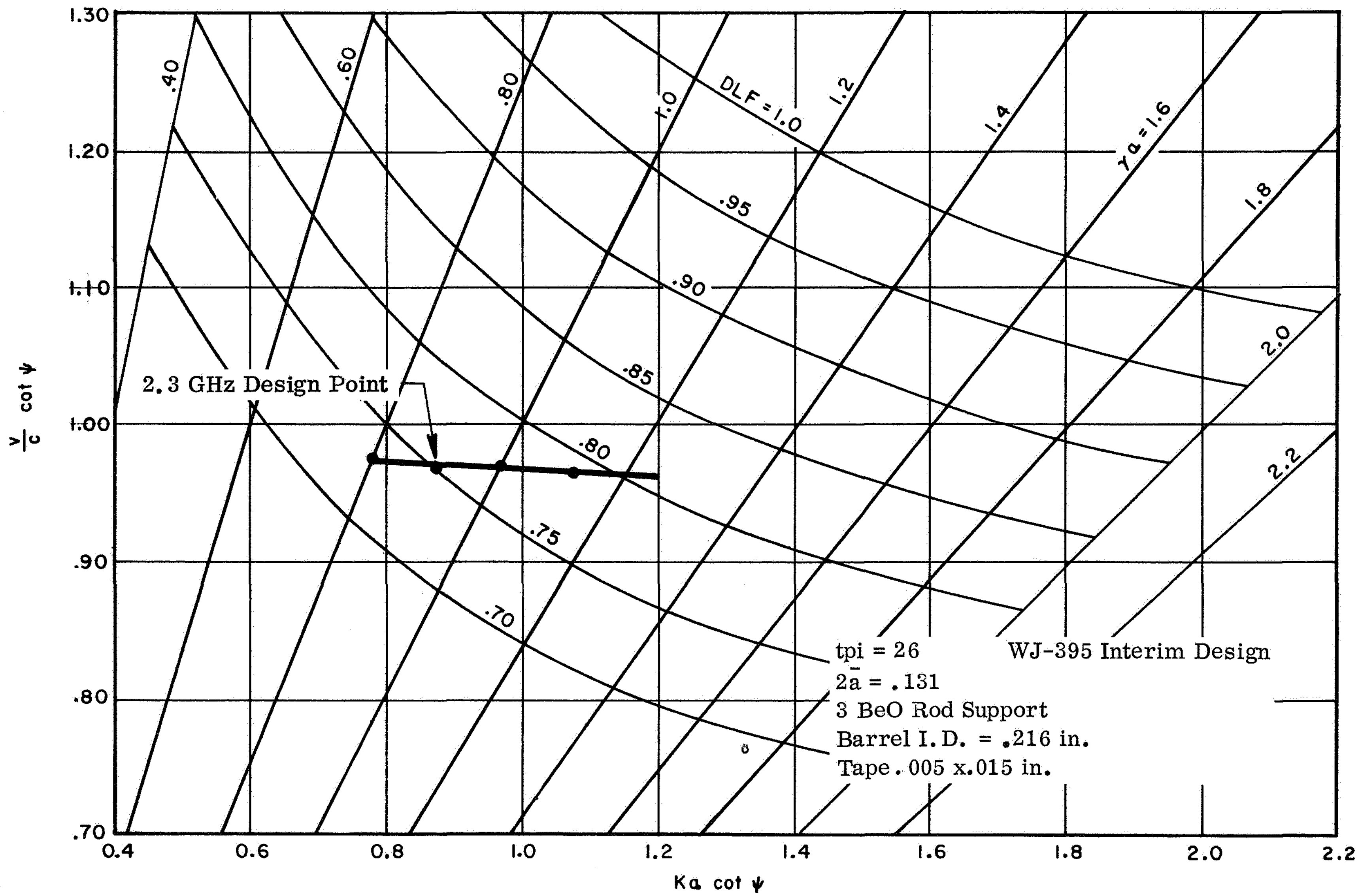

Fig. 2 - Normalized helix dispersion curve showing the WJ-395 interim design point. The DLF and γa are shown as parameters.

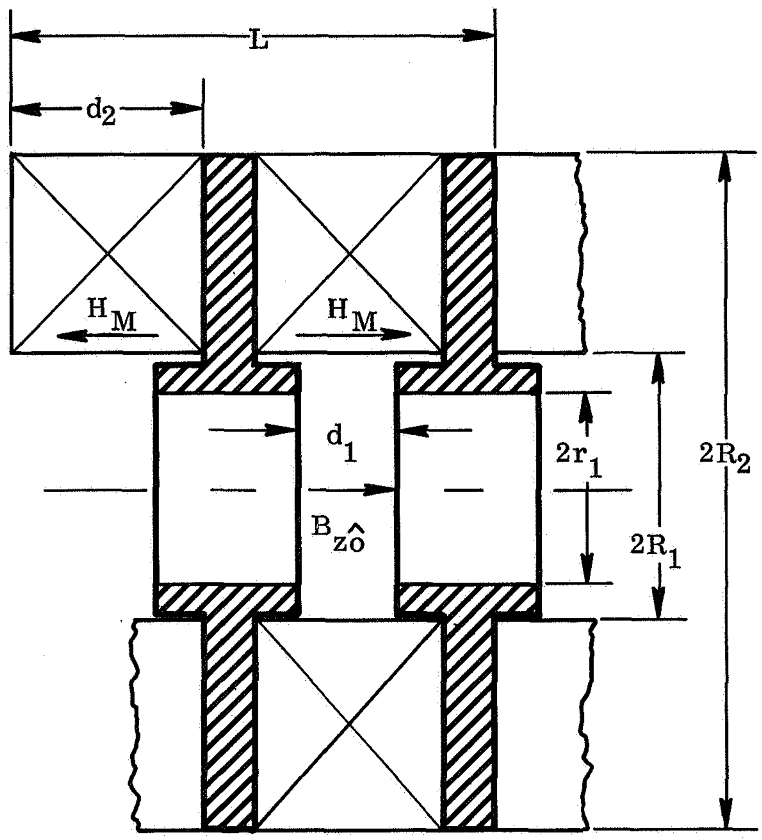

Fig. 3 - Sketch of PPM stack illustrating geometry as listed in Table IV.

TABLE IV

Design Parameters of PPM Focusing System

	Interim Design	Est. Final Design
Magnet Material	Alnico 8	Alnico 8
Brillouin Focusing Field, B_{br}	386	354
Peak PPM Field, $B_{\hat{zo}}$	826 gauss	707 gauss peak
Magnet period, L	.428	.354 inch
Pole Piece I.D., $2r_1$	.237	.237 inch
Magnetizing Force, Hm	1000	1140 oersteds
Magnet I.D., $2R_1$	.286	.282 inch
Magnet O. D., $2R_2$	.520	.488 inch
Magnet Thickness, d_2	.189	.152 inch
Gap Length, d_1	.091	.071 inch
$\lambda p/L$ (1)	4.1	5
$\lambda s/L$ (2)	2.7	3.58
$\lambda s^*/L$ (3)	1.64	2.13

(1) λp is the plasma wavelength of the beam.

(2) λs is the no-drive scalloping wavelength of the beam.

(3) λs^* is the scalloping wavelength of the slowest electron under saturated RF drive.

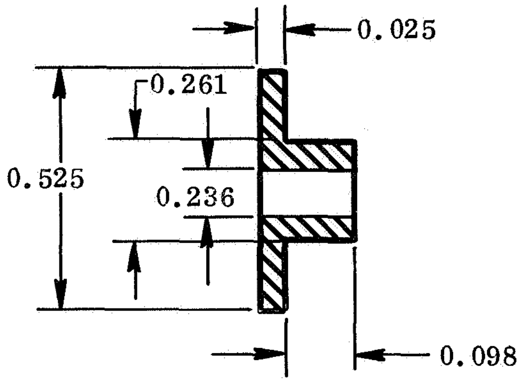

Fig. 4a - A single hub drawn pole piece. The hub can not be successfully drawn to the required.098 in. length.

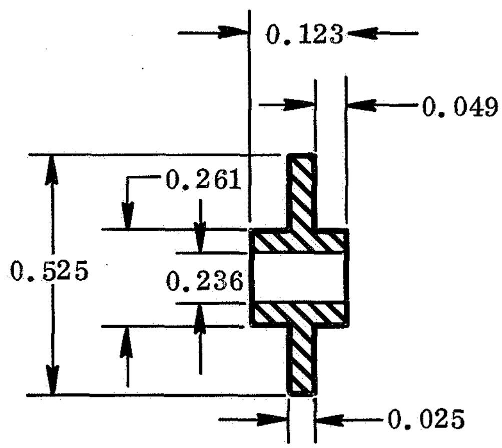

Fig. 4b - A machined pole piece.

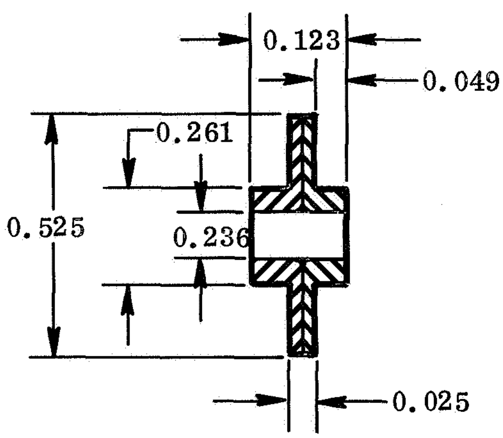

Fig. 4c - Two single hub pole pieces formed by drawing the hubs to replace the machined pole pieces above.

Tube Body Construction

Figure 5 shows a cross-sectioned drawing of the tube body and helix. The helix is .005 by .015 in. tungsten tape. The helix is supported by three 0.040 inch BeO rods. The barrel is triangulated in a fixture for helix assembly insertion. The rods and helix assembly are placed in the barrel and the barrel is released from the fixture, thus tightly holding the helix in place in the barrel. The magnetic PPM pole pieces are slid over the barrel after the helix assembly has been placed in the barrel.

Gun Design and Gun Envelope

A perveance .51 microperv convergent flow electron gun was designed to have a beam diameter of .071 inch. This gun can be used with both the interim tube design and the final tube design. The gun was designed so that the cathode loading is 175 mA per square centimeter, which is compatible with long tube life.

Table V lists the design parameters for the gun, both for the interim tube design and the final tube design. The beam edge potentials were determined in an electrolytic tank by adjusting the focus electrode geometry. Fig. 6 shows a bell jar gun tester used by the Watkins-Johnson Company to test new electron guns. The gun was tested in this beam tester for the location and size of beam minimum. The radial velocities of the electrons at the beam minimum position were also measured. Some results of these measurements are also shown in Fig. 7. The mechanical design of the gun is shown in Fig. 8.

Collector Design

It is required that the WJ-395 be conduction cooled. It is also required that the collector be depressed in order to achieve the maximum overall tube efficiency. Since the helix operates at ground potential, the collector will operate below ground potential and must be electrically insulated. It must also have good thermal conductance for removal of the heat. A collector design was selected which is very similar to the design used in several other tubes at Watkins-Johnson Company. This collector consists of a ceramic insulator which provides electrical insulation and a reasonable thermal conductance in order that the collector heat may be removed. Fig. 9 shows the collector design where the ceramic is used as both an electrical insulator and a thermal conductor. The heat is removed from the ceramic to the capsule by means of a thin silicone base heat conducting material. The layer is kept thin so that the temperature drop will be small.

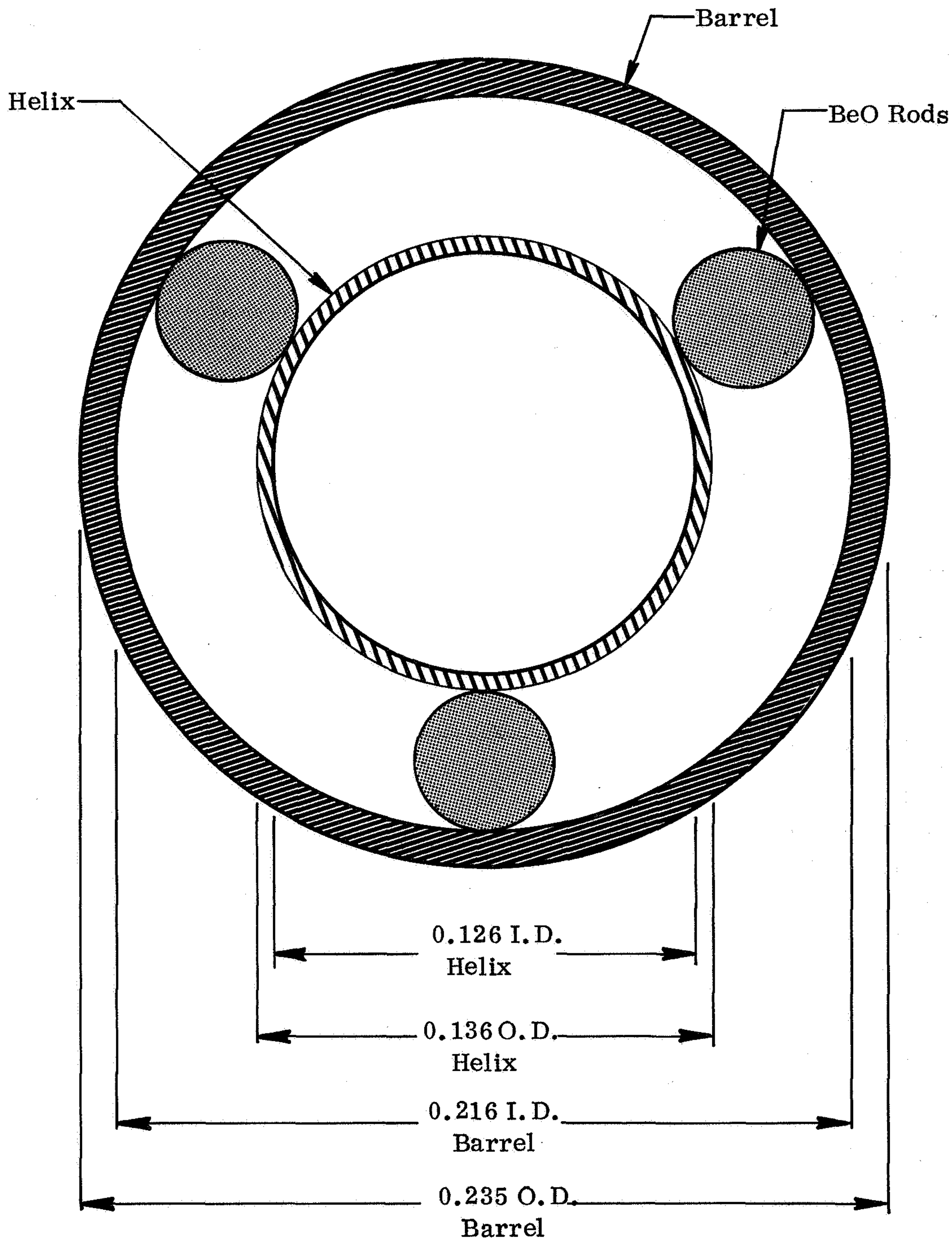

Fig. 5 - Cross sectional drawing of .015 x.005 inch tape helix supported by .040 inch BeO rods inside a .216 inch I.D. barrel.

16964

TABLE V

List of Design Parameters for Electron Gun

	Interim Design	Est. Final Design
Perveance, $\mathbb{P}$	$.51 \times 10^{-6}$	$.51 \times 10^{-6}$
Anode Voltage, V_o	3360 volts	2850 volts
Beam Current, I_o	.099 Amps	.078 Amps
Beam Current Density, J_o	3.86 Amp/cm^2	3.04 Amp/cm^2
Cathode Current Density, J_c	.222 Amp/cm^2	.175 Amp/cm^2
$2r_{95}$(1)	.071 inches	.071 inches
Ratio Beam Diameter to Cathode Diameter, r_{95}/r_c	.21	.24
Gun Area Convergence, A_{95}/A_c	17.4	17.4
Cathode Diameter, $2r_c$	.296 inch	.296 inch
Gun Thermal Parameter, $\frac{\mathbb{P}V}{T}$	1.727	1.465
Ratio Cathode to Anode Radius of Curvature, $\bar{r}_c/\bar{r}_a$	2.31	2.31
Normalized Distance Parameter, $(-\alpha a)^2$	1.2095	1.2095
Cathode Half-Angle, Θ	16.67^o	16.67^o
Cathode Radius of Curvature, $\bar{r}_c$	.516 inch	.516 inch
Anode Radius of Curvature, $\bar{r}_a$	.223 inch	.223 inch

(1) $2r_{95}$ is the beam diameter containing 95 percent of the beam current.

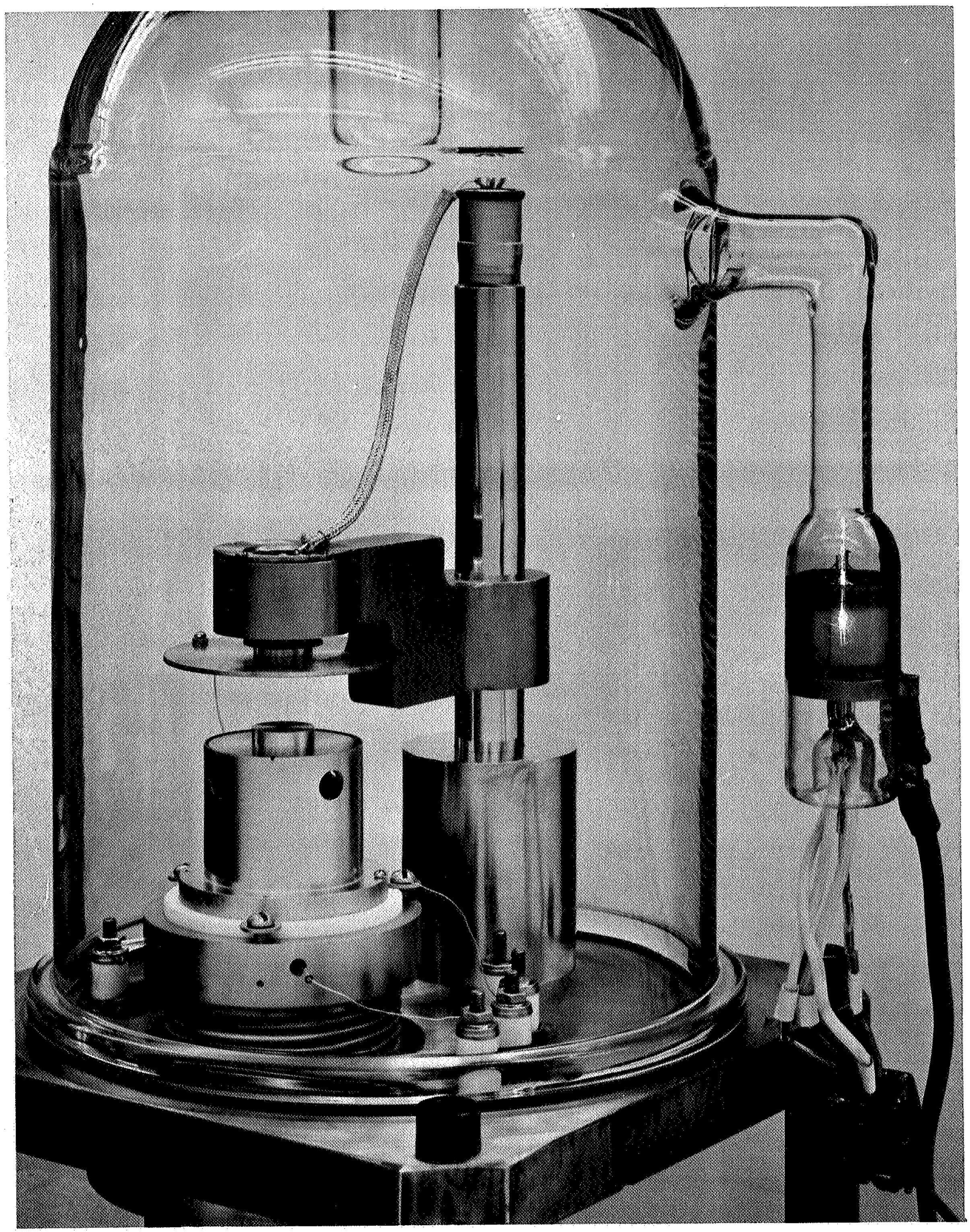

Fig. 6 - Photograph of the bell jar gun tester used to evaluate the $.51 \times 10^{-6}$ perveance electron gun for use on the WJ 395

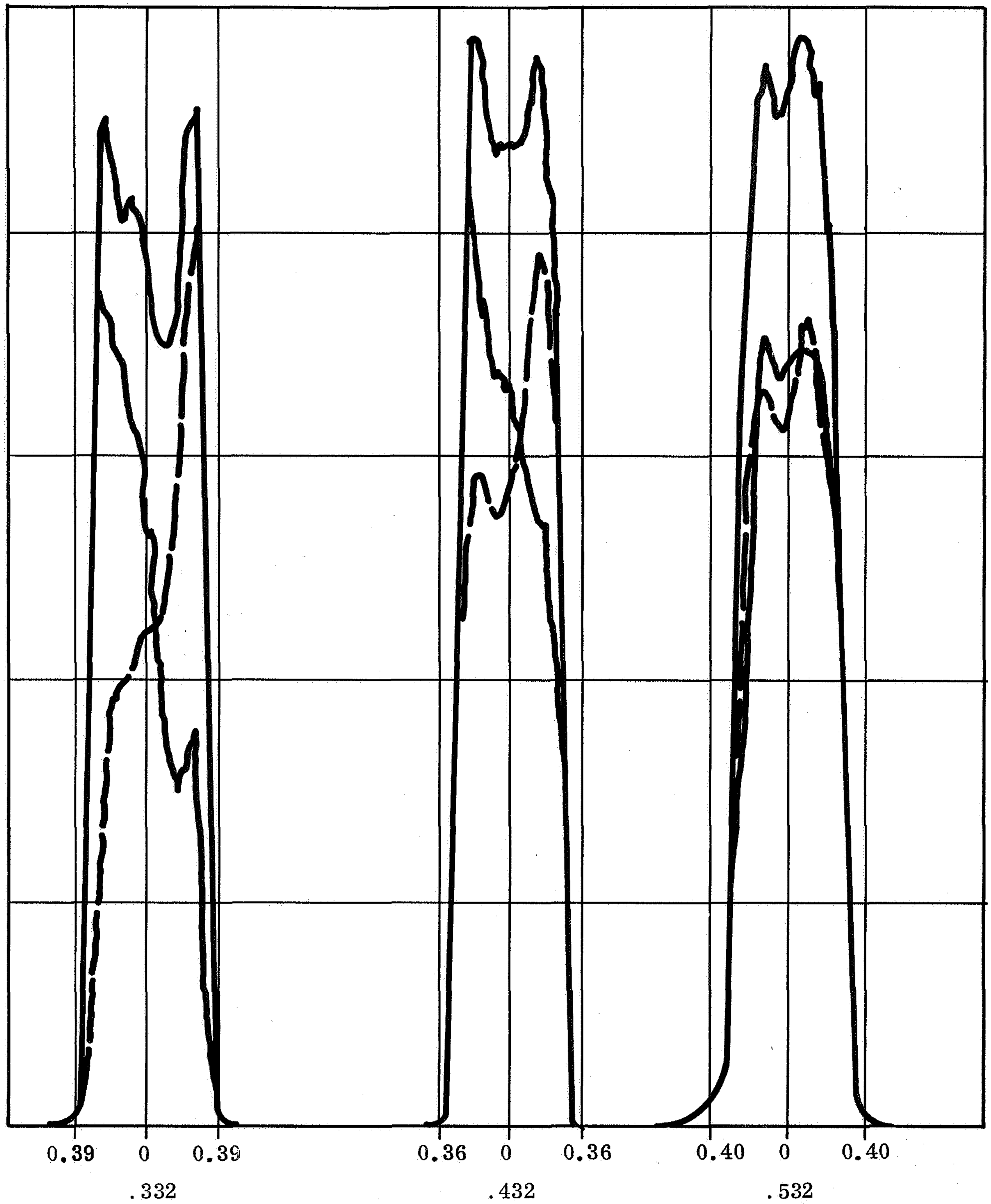

Fig. 7 - Measured beam current density profiles taken at various axial positions for the perveance 0.51×10^{-6} gun. The ordinates are current density relative to the maximum value at the beam minimum. The abscissas are labeled in inches. The number under each figure indicates the distance in inches between the anode and the position where the profile was taken. The two smaller profiles at each axial position are the currents from each half of a split collector. The larger curve is the total current. Zero radial velocity is indicated by superposition of the two smaller curves.

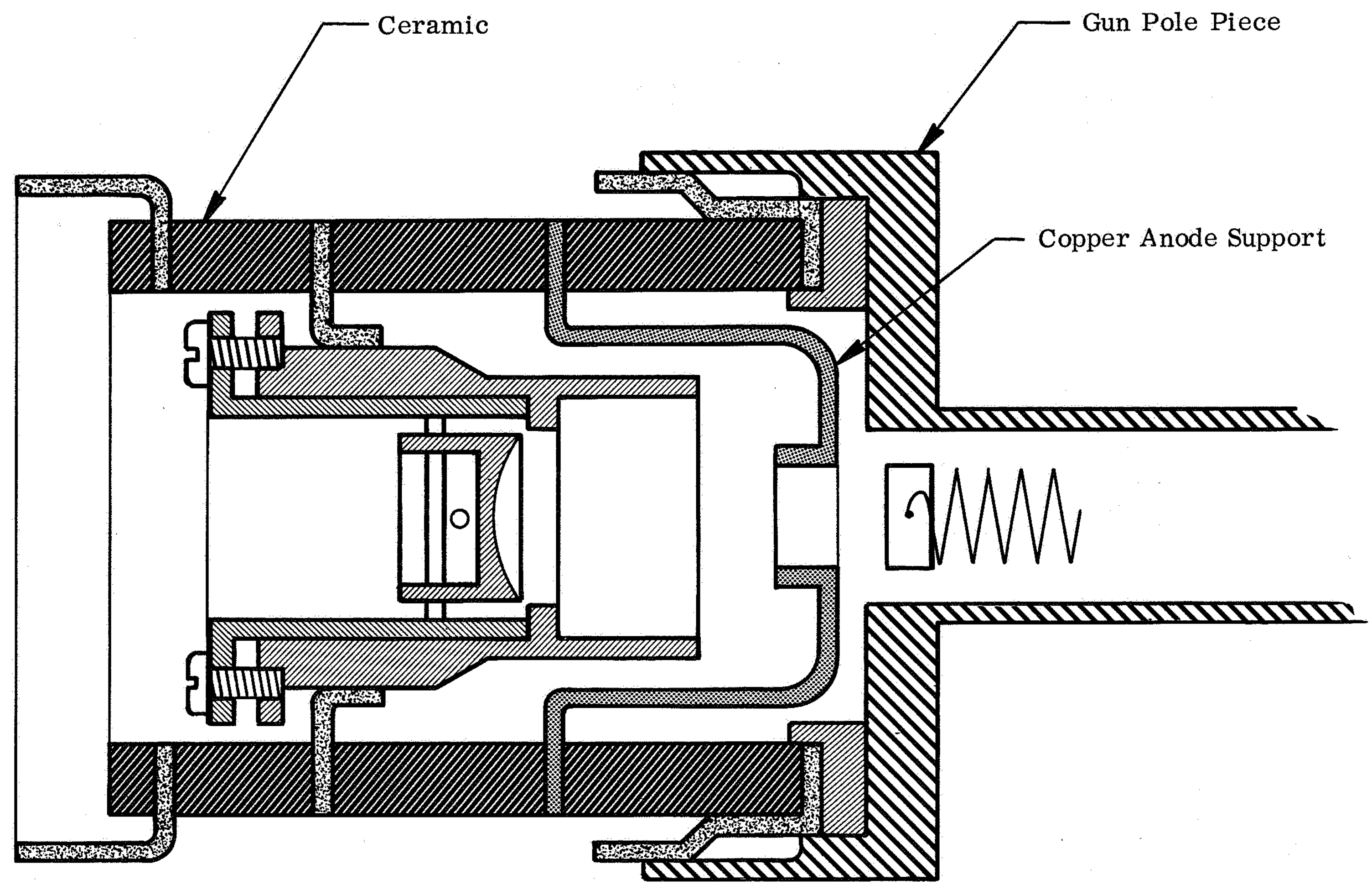

Fig. 8 - Sketch of mechanical gun design used on the WJ-395.

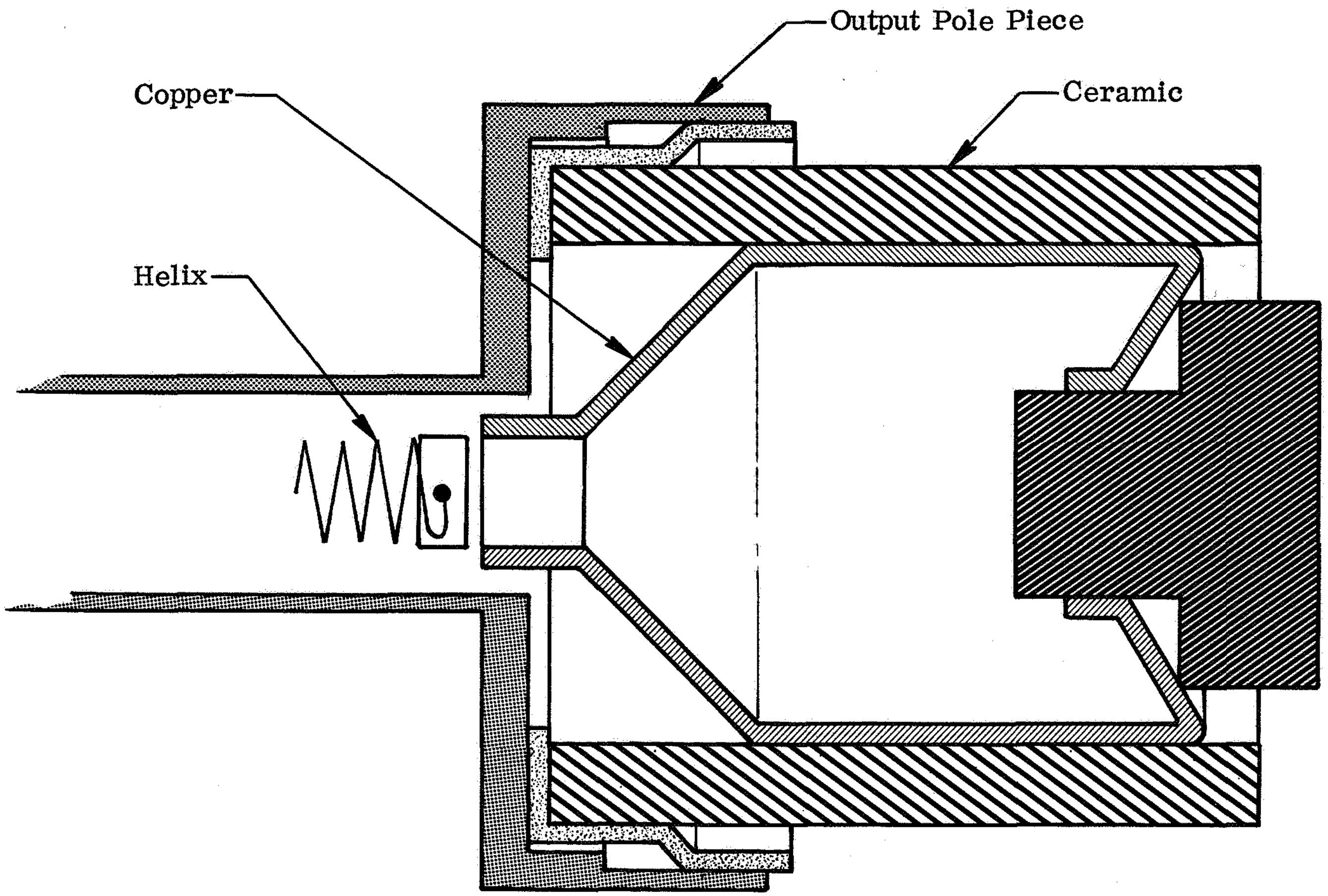

Fig. 9 - Sketch of the mechanical design of the collector for the WJ-395 TWT.

Capsule Design

The interim capsule design is shown in Fig. 10. The tube will be placed as shown in the capsule. The tube will be potted into the capsule and the heat dissipated in the tube removed by means of bolting the capsule to a heat sink.

Accomplishments During the Quarter

During the quarter, the interim tube electrical design was completed. This includes the design of the helix, electron gun, collector and the PPM magnetic focusing system. The electron gun was designed, constructed and tested in the bell jar beam analyzer shown in Fig. 6. The mechanical design was also completed. It was decided to build a single helix tube first in order to check out the power handling capabilities, focusing, and mechanical designs. A helix was constructed and tested to determine the phase velocity and the helix TPI required for the interim tubes. The jigs and fixtures necessary to construct the tube were designed, parts for the interim tubes ordered and parts have been arriving from the shop as of the end of the report period. Other materials, such as the ceramics and magnets, have been ordered from suitable vendors.

Items to be Accomplished During the Next Quarter

During the next quarter the construction and testing of three tubes is planned. During this period the early construction problems will be eliminated and further work will be done on the preliminary capsule design, with preparation to do some environmental testing.

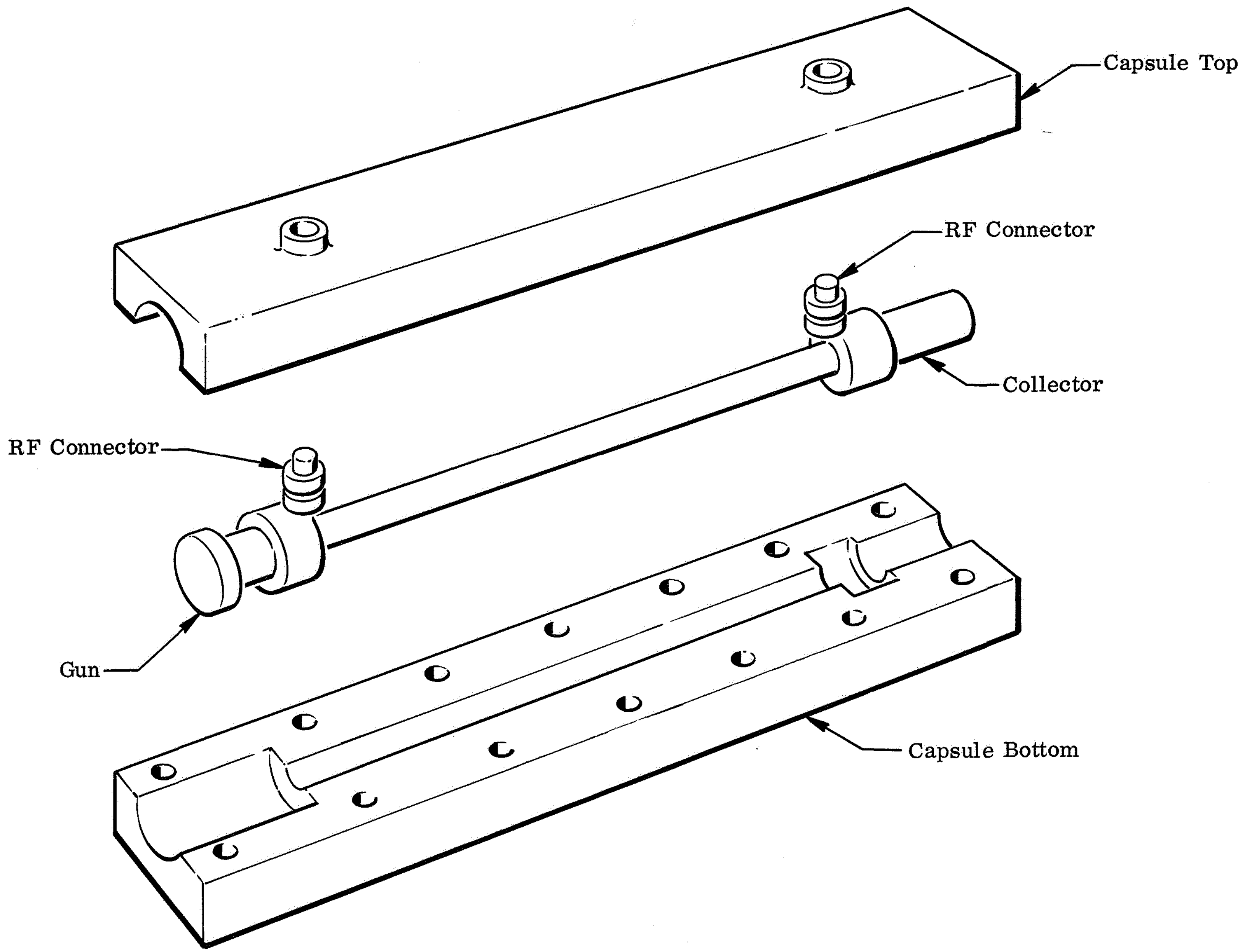

Fig. 10 - Sketch shows the capsule and tube in an exploded view.